GeoMapper Universal Digital Pen Mapping System for Geological, Mining, Exploration and Environmental Mapping with a Point and Click Legend Maker and Project-based File Manager

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ABSTRACT

GeoMapper is a proven digital mapping system designed from the standpoint of the field geologist for rapid acquisition of necessary digital mapping skills and production of their first map in the shortest possible time. GeoMapper is in use in academic, mining and environmental applications and follows the mapping system developed by the former Anaconda Company in Butte, Montana. Regardless of the application area, the transition from traditional paper mapping to direct real-time digital mapping is not difficult as our visual user interface is logical and largely self-explanatory and breaks mapping down into commonly used features such as contacts, faults, veins, colored areas of each formation, outcrops, and structural symbols such as strike and dip. GeoMapper's architecture implements mapping tools with button icons in contrast to pull-down menus and shows only the necessary set up commands to begin mapping with the variety of mapping tools expected in geology. Furthermore, the buttons are shown in the general sequence of their use so scientific logic naturally guides the selection of mapping tools as one proceeds as usual to map in a desired fashion. Professional mining and exploration mapping presents challenging requirements for both software and hardware. The software must be extremely user friendly and robust to the point of being nearly "bullet proof" as field conditions are often hard and time is of the essence. Hence, essentially every step in digital mapping has to be considered "mission critical" by eliminating the possibility of not knowing what to do next nor freezing up the computer. Towards these ends, GeoMapper provides a pre-loaded general geology mapping legend. The generic startup legend (GSL) of GeoMapper is language independent and contains standard structural symbols (strike, dip, faults, and contacts as well as their level of certainty), lithologic patterns, formation colors, and ore deposit mineralization styles (veins, veinlets, disseminations, breccia, and stockworks), wall rock alteration facies and mineralogy in

both sulfide and oxide weathering zones. A visual legend maker (VLM) is provided within GeoMapper that requires only point and click skills and facilitates immediate personalization of the generic legend by entering local formation names, lithologies, and desired colors of formations. Besides mapping in plan view, GeoMapper supports full mapping capabilities in cross section orientation. For underground mine mapping, base maps can be imported as ground lines with survey marker coordinates for setting up a laser. For surface mapping, digital topography and/or high spatial resolution color ortho-photos are used in combination with sub-meter DGPS. Numerical data base information (eg. strike, dip, and samples) are exported into utility programs such as Rock Works for stereographic plotting, geotechnical failure analysis or for GIS output and map production. Direct real-time digital mapping circumvents the need for digitizing paper maps made with traditional methods. Consequently, a considerable savings in time is realized in producing maps while providing immediate digital records and shared data bases to other users.

INTRODUCITON

Currently, digital mapping technology is evolving rapidly through a challenging transitional period between lingering use of paper and conversion to highly promising digital media of vector topography and raster images and electronic mapping methods using pen stylus input supported by sub-meter DGPS and laser range finders. Although there is widespread acknowledgement that digital methods of the Information Age will one day replace the traditional paper media, relatively few groups in industry, agencies or academia have entered this field so far. These early innovator institutions who have invested in the growth of digital mapping and were bold enough to experiment with a new technology have experienced both the excitement of using a powerful new technology as well as the frustration of dealing with the limitations of early products of software development and hardware systems adapted to new areas of application. Here we summarize the present status of our development and field capabilities of an integrated geological mapping software system called GeoMapper to meet the varied scientific needs of geologists working in industry, agencies and academia. GeoMapper was developed by us within the Digital Mapping Lab of the University of California, Berkeley Earth Resources Center.

Motivation for GeoMapper

Geological mapping in the field or underground is sometimes as demanding a task as one would imagine ever doing more than once. Even though we practitioners of earth science often thrive on such invigorating outdoor work amidst the grandeur nature often provides, we often labor under severe conditions and stringent time demands. Given this happy ordeal in the field, our craft is not for everyone. Only the highly motivated and strong survive the physical rigors of the work place, the isolation in the field and the vagaries of the economic employment cycles. While challenging physically, mapping remains the main reason for our enthusiasm for geology. The intellectual activities in quantitative observation are richly-complex and offer a profoundly interesting natural science view of the world where our eyes still provide the seminal information about rocks which are nature’s archive of geological history and the evolution of process. The mapping system we use to support our work must serve our needs very well if we are to

function successfully and maintain our enthusiasm as well as earn the continued support of our host institutions by creating useful maps and interpretations. Given the realities of mapping, anything that impedes our work is soon abandoned. Consequently, conversion from paper base maps to digital mapping systems has not been easy. Commercial graphics programs barely approach the level of visual sophistication required by mappers and have little data base management functionality. Alternatively, 2-D and 3-D GIS software, while offering powerful utilities in visualization and numerical calculation, extracting features and outputting maps from existing data, they lack front end data capture engines to map new features directly in the field. Hence, the primary role of a geologist *as a scientist in the field*, could not be accommodated with commercial software. We recognized the need for a practical and portable field mapping system some five years ago, and have a system now working in a variety of application areas.

Approach

Being both geologists and computer programmers ourselves with mapping experience in a variety of applications areas in industry and academia, we approach digital mapping from the standpoint of *knowing* what has to be done to make a useful map and implementing those steps using portable computers and digital devices. We know that time in the field is limited and hence, every step must produce useful lines, areas, symbols, notes and numerical data on a map. We also know *how* we geologists want to map: the sequence in activities and priorities in making decisions; the *flow* of the work. Our training in field mapping has many common attributes which we do not wish to lose. We do not want to have to yield to awkward computerized mapping steps just because a computer program would like us to work a certain way. In short we already have a procedural system in place. The training of geologists with computers usually focuses on using programs rather than on programming. Hence, the mapping software used must conform to our traditional ways of mapping and *not* require knowledge of programming. In order to produce a viable user friendly mapping system compatible with geologist's training and professional needs, we have designed GeoMapper from the field requirements backwards rather from commercial graphics capabilities forward. In fact in our latest version of GeoMapper Universal we have eliminated the need for a user to know programming at all. Furthermore, rather than reinvent the wheel, GeoMapper combines our own mapping protocols, visual user interface, and new computer programs with the most powerful digitizing tablet available, PenMap by Strata Software which also handles device drivers for lasers and GPS units, data base files, and primitive graphics (line, points, areas). Most importantly, we have added in GeoMapper a geological legend maker anyone can understand, use and start mapping without having to know even macro language programming.

History of Digital Mapping

The term, "digital mapping," has referred to a variety of activities involved in map production: cataloging existing maps in digital form for retrieval (Soller et al, 2000), devising a lexicon of geological names (Stamm et al, 2000), GIS information management (Brodaric, 2000), cartographic symbolization (Soller and Lindquist, 2000), production of final maps after scanning paper based maps (Stanford and MacKubbin, 2000), compilation and digitization (Furr, 2000), retrieving information using GIS (Fryer

et al, 2000) and visualization (Morin, 2000). Progress has been faster in developing digital technology to support office map production than in actual mapping in the field. Our work is an effort to help close the gap between the obvious promise and the practicality of digital mapping.

The status of field data collection using digital mapping systems as opposed to digitization of paper maps, was summarized by Kramer (2000) including our progress developing GeoMapper within the Earth Resources Center of the University of California, Berkeley (ERC) (Brimhall, 1998, 1999, 2000; Brimhall and Vanegas, 2000, 2001; Vanegas et al, 2000). Brimhall and Vanegas (2001) summarized the development of the latest version of GeoMapper called GeoMapper Universal now ready for general distribution. The GeoMapper systems were tested, refined and improved through their use in both surface and underground geological mapping and function well over small to large scale maps in a wide spectrum of geological environments. GeoMapper has been used in instruction at UC Berkeley for three years in undergraduate and graduate field classes. GeoMapper has also been used in the ERC in support of abandoned mine characterization using hyperspectral visible light/infrared methods supported by real-time GPS and laser positioning (Montero-Sanchez and Brimhall, 1998, 2000; Montero-Shanchez et al, 1999; Takagi and Brimhall, 2000) including mapping from helicopters.

Barriers of Acceptance of Digital Mapping

ERC digital mapping research and development projects with Codelco Chile, Placer Dome Exploration and WMC Australia Olympic Dam provided much knowledge about the nature of the modern mapping discipline in industry. Especially revealing aspects have been desirable features and the breadth of technical demands on the systems covering a spectrum from new mappers in the field mapping classes at UC Berkeley to experienced professionals in industry. Especially important is (1) the need to find ways to engage users whose backgrounds in computing is limited although they may be excellent experienced mappers. This work also revealed (2) a number of distinct barriers to acceptance of digital mapping that are surprisingly similar to those recognized for acceptance of mobile computing in the healthcare industry in daily practice (Stetson, 2001). Acknowledgement and resolution of shortcomings is essential to advancement and acceptance of new technology.

Learning From Mapping Experience

Geological mapping has many similarities to medical practice both in terms of technical issues in map production in the office and performance in the field. Highly-trained scientists and engineers conduct their professional discipline by actively seeking information, making instantaneous interpretations and decisions. Contrary to common perceptions, the gravity of the interpretation by field mappers is often no less than in medicine. Our scientific conclusions often can affect the lives of numerous people and the efficacy of financial investment in the billions of dollars as in construction, water resource management, mining, environmental applications and emergency intervention and planning for natural hazards like earthquakes, floods and landslides. Consequently, a digital mapping system must meet the workflow needs of this user group if they are to work with confidence and facility and to supply vitally-important geo-spatial

information and interpretations. Software systems designed largely for the office environment of map production cannot do this effectively. Finally, since mapping addresses three dimensional exposures, existing mapping systems that support only mapping in plan view leave a large gap in required mapping capabilities.

THE PROMISE OF DIGITAL MAPPING

If proven to be practical, economical and flexible in terms of mapping in plan or section, portable integrated field mapping systems supported by GPS, lasers and digital cameras could soon become commonplace not only for mapping on land, but underground, from the air, on the sea bed, and ultimately in space on other planetary surfaces, first robotically and then by astronauts. Resource sustainability and proactive environmental management on a global basis have become imperative societal goals making geo-spatial phenomena the central scientific infrastructure. However, for digital mapping to realize its potential to serve these needs as a truly enabling generative technology worthy of becoming widely adopted and ultimately replacing the traditional paper methods while creating valuable new knowledge about the earth, a significant challenge remains to be overcome in software design and functionality. The present limitations stem from not fully acknowledging the scientific needs of practitioners, especially as being distinct from technological needs alone. We need to manage new technologies more effectively in doing science. Here we address only the issue of workflow and throughput, and view the remaining problems of cost and vendor incompatibility as being dependent upon the digital mapping systems first proving to be useful before they become commonplace. We hope that our system will help establish standards that will speed this process.

The Different Challenges of Science and Technology

Science and technology are alternative perspectives of knowledge and especially of use of instrumentation. Science seeks a deep understanding of natural phenomena while technology uses advanced technical means to serve human ends. A geological map is fundamentally an information-rich *scientific* document although it is produced technically. Digital mapping technology is rightly concerned with technical issues, yet another important dimension of the map is its scientific knowledge. This scientific knowledge is created by a highly-trained scientist with needs in the field quite distinct from those of office personnel who produce the map and deal with data base management. In some organizations, the mapper and map producer are one in the same individual. In advancing GeoMapper, we have viewed our challenge then to be in constructing a software architecture that above all else enables the scientific mission in the field and provides a compatibility with subsequent map production needs so the two activities become mutually supportive.

We perceive two main challenges in mapping software design. The first is creation of an effective visual user interface to manage mapping tools, graphics and files for local geology in such a way that the system being used actually *feels* to a geologist like normal mapping and produces professional quality maps at a rate sufficient to make the system cost effective by eliminating unnecessary paper media steps. Secondly, the software also needs to offer a practical means of incorporating the essential stratigraphic

and lithological features of a wide range of geological terranes so that each geologists can begin new projects without delay using a newly-created legend. With respect to both challenges, it is impractical to require users to know even macro language programming to create a usable visual interface for their work. The visual user interface constitutes the entirety of the link between their professional scientific skills, normal procedures of mapping and the new digital tools at their disposal. With his interface they confront the realities of nature to be mapped; therefore it must be familiar, comprehensive, easy to use and easy to personalize to local setting otherwise it is a formidable barrier.

GEOMAPPER UNIVERSAL

It is essential to realize that when we geologists map, we are in fact practicing our scientific discipline in the field through observation, exercising reasoning and using the scientific tools intrinsic to geology. A visual user interface must provide much more than graphic tools like points, lines and areas, colors and data bases in a generic visual user interface. Here we present our recent advances in designing the second generation of GeoMapper (GeoMapper Universal) with totally new visual user interfaces for a geologist to readily personalize the mapping legend for local geology on a project basis, learn the mapping system and readily conduct digital geological mapping using the scientific methods of field geology (Brimhall and Vanegas, 2001) including mapping in section view. Unless digital mapping capabilities meet both technological and *scientific* requirements of field geology as it is practiced today and are robust and easy to use, adoption will come only slowly after each barrier to use is removed. Present paper mapping capabilities with traditional methods are immensely powerful and the tools are simple and inexpensive. By practical necessity, the tools have evolved to the point of near perfection for what they present: an inexpensive, portable, light weight paper-based medium proven by the test of time to offer the *essential* information of science at the lowest cost. However, paper mapping being an analog process, is not inherently well-adapted to incorporation into the digital revolution and the information age. Here we consider what paper mapping is, where it came from, and how best to translate mapping into a viable digital protocol.

EVOLUTION OF MAPPING AS THE SCIENTIFIC BASIS OF GEOLOGY

Mapping using paper media has been a core discipline of professional geology in the U.S. for a century in federal and state agencies, industry and academia. Traditional mapping methods have been proven globally in all types of field conditions, varied geology, and project scope from rapid reconnaissance to detailed mine mapping. Digital mapping must meet the quality of the traditional standards.

United States Geological Survey

In the U.S. mapping has evolved considerably from scientific support of mining by the U.S. Geological Survey (Lindgren and Turner, 1894, 1895) which set an international standard of excellence in surface mapping and color folio map production.

Anaconda Mapping System in Butte Montana

Industrial geologists, initially in the Anaconda Company in Butte Montana (Peters, 1987), developed standardized mapping procedures for underground vein mines forming the basis of compilation of plan level maps (Figure 1), serial cross sections and three dimensional geological models used in exploration, development and resolution of vein apex mining law litigation (Brunton, 1901; Linforth, 1914; Sales, 1929, 1941; McLaughlin and Sales, 1933; McKinstry, 1948). Veins and intrusive igneous rocks were mapped in drifts, stopes and crosscuts showing relative age relations by offsets.

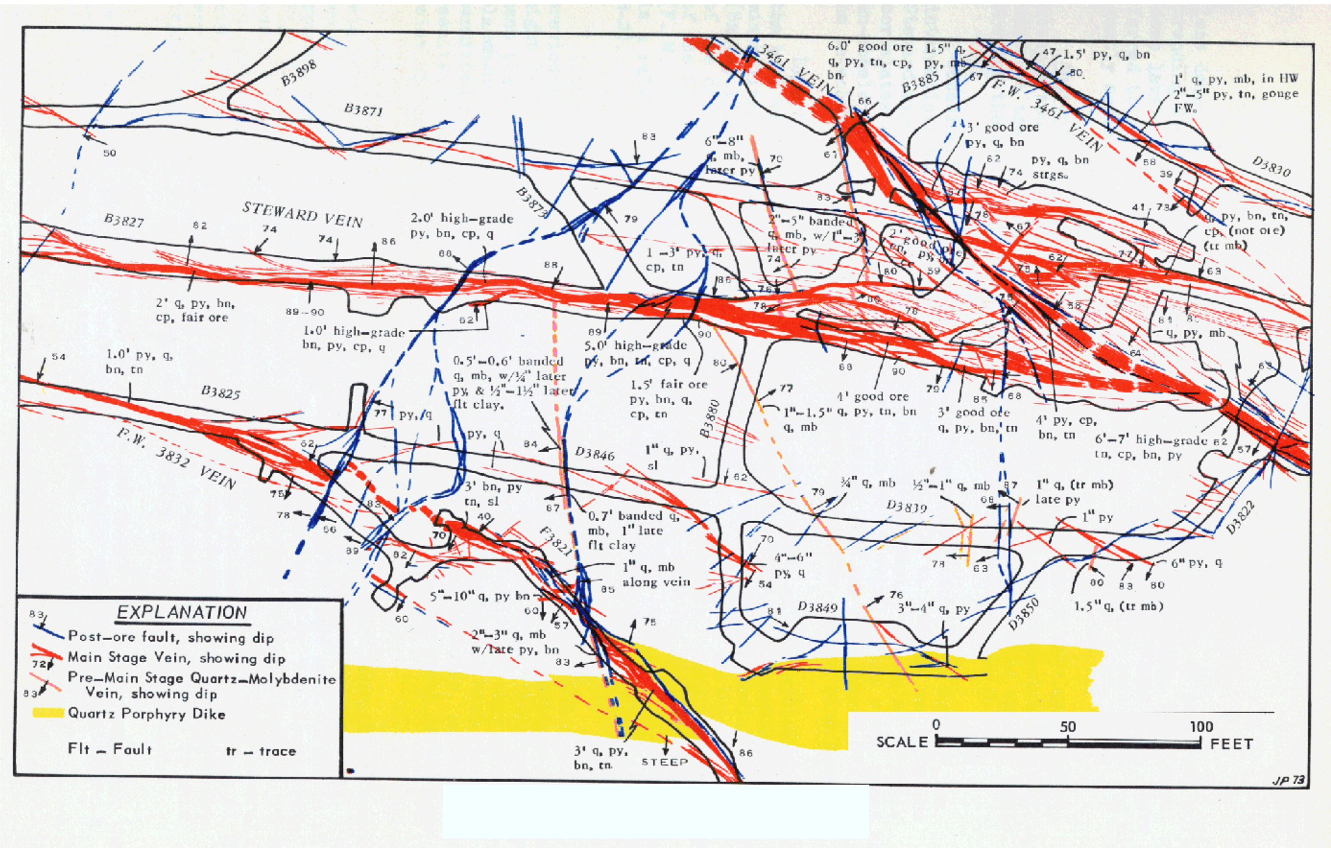

Figure 1. Steward Mine, Butte Montana, part of the 3800 level mapped by J. M. Proffett (1973).

Alteration mapping of advanced argillic, sericitic, and white and green argillic envelopes aligned with and co-axial to causative hydrothermal veins provided genetic relationships to relate mineralization as copper content (%) to wall rock alteration processes (Figure 2) (Brimhall, 1973) necessary to interpret multi-stage magmatic-hydrothermal events and determine the source(s) of metals as well as inferring the geochemical conditions and fluid chemistry.

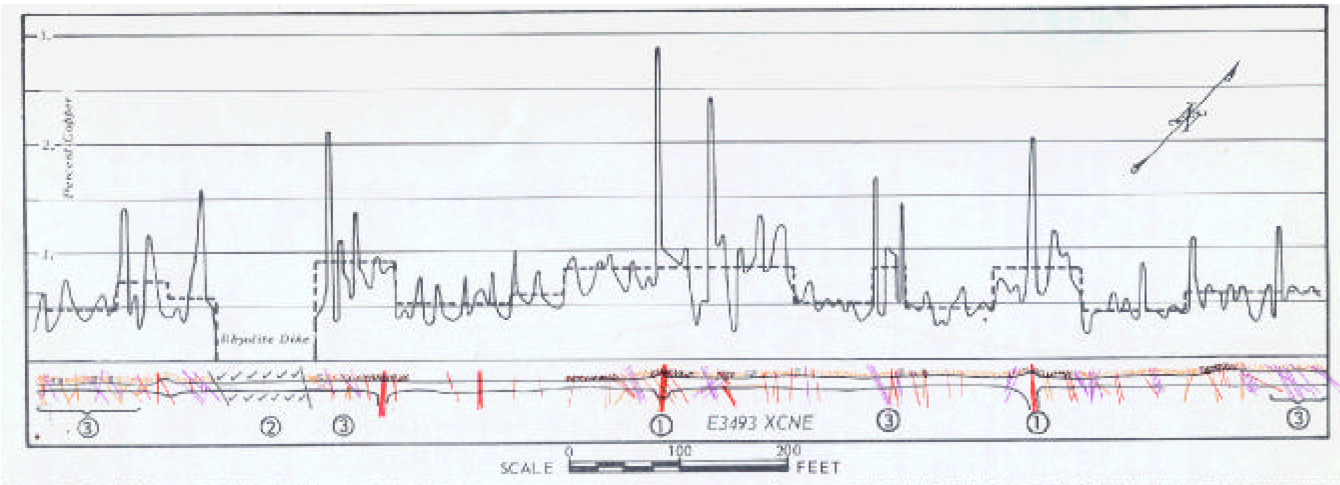

Figure 2. Steward Mine, Butte Montana, part of the 3400 level mapped by G. H Brimhall (1973). Copper assay versus distance. Sericitic alteration is brown colored, argillic is orange. Main Stage veins are red, and pre-Main Stage veins are purple. Wide zones exit with considerable copper but only pre-Main Stage veins.

From hundreds of such maps, the chronology of all magmatic and hydrothermal processes was synthesized and translated into a standardized geological mapping legend of the Butte District (Figure 3) (Miller, 1973).

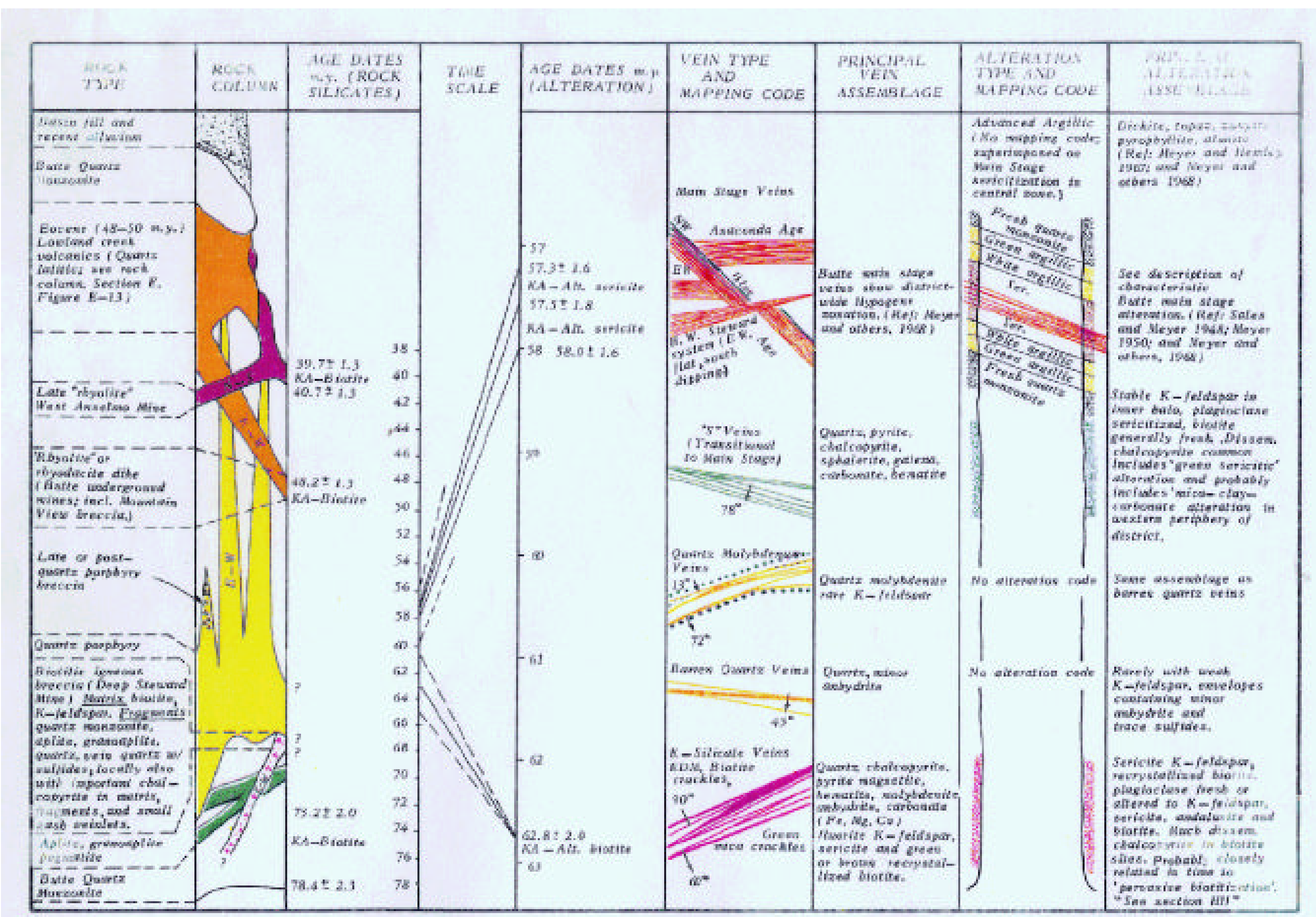

Figure 3. Generalized intrusive, vein, alteration sequence and mapping symbolism Miller, 1973)

The Anaconda mapping system created in Butte evolved over almost a century (Figure 4) to a system widely emulated elsewhere because of its simplicity and utility.

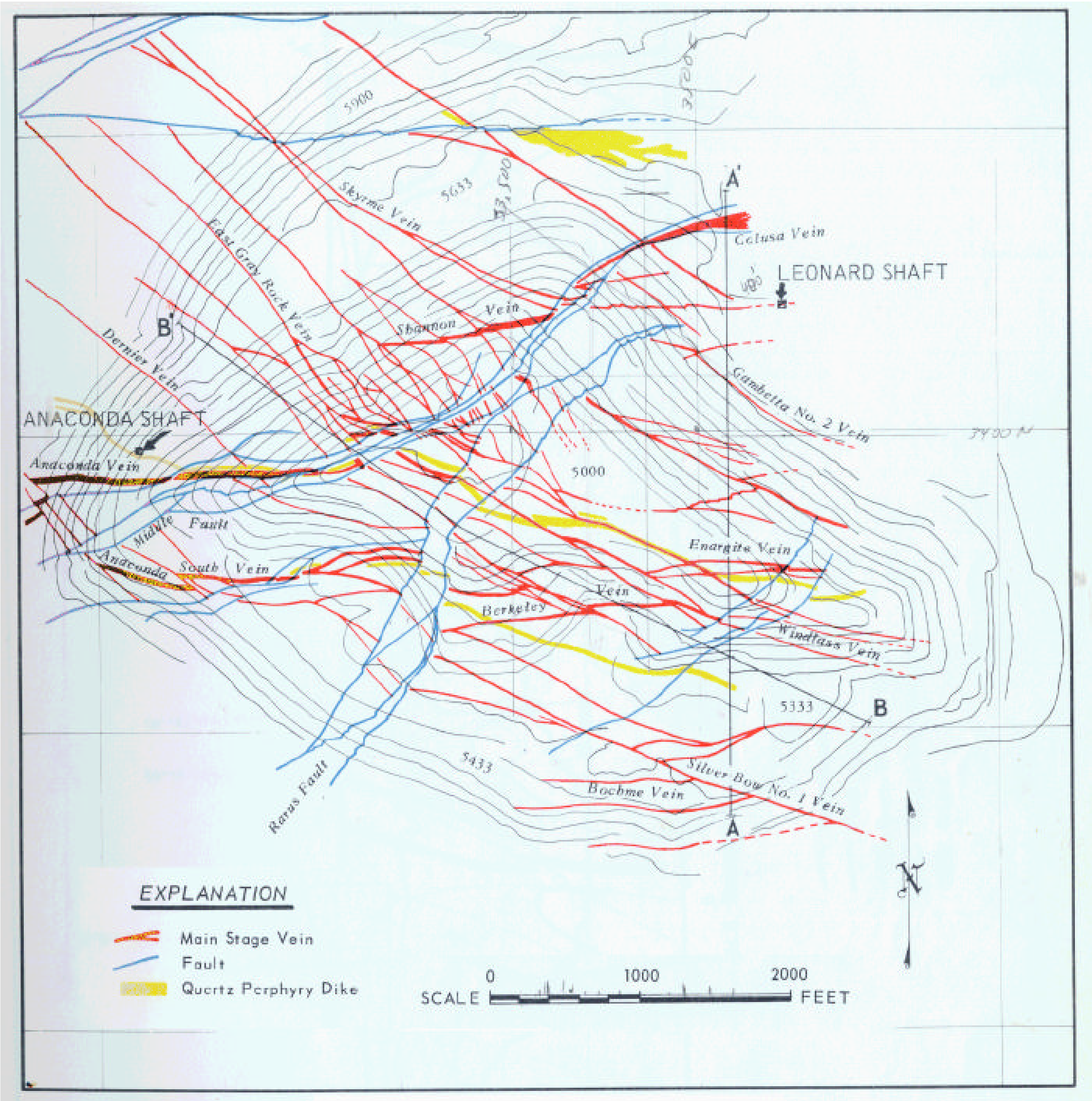

Figure 4. District geology of the Berkeley Pit, Butte, Montana, showing quartz porphyry dikes, Main Stage veins and faults (McClave, 1973).

The mapping system was expanded through mapping other mining districts of the company including the El Salvador mine in Chile, Yerington in Nevada, Carr Fork in Utah with contributions by many Anaconda mine and exploration geologists. District-scale compilations provided guidance for mine development and creation of genetic models for space-time-mineralization-alteration in porphyry copper deposits (Figure 5).

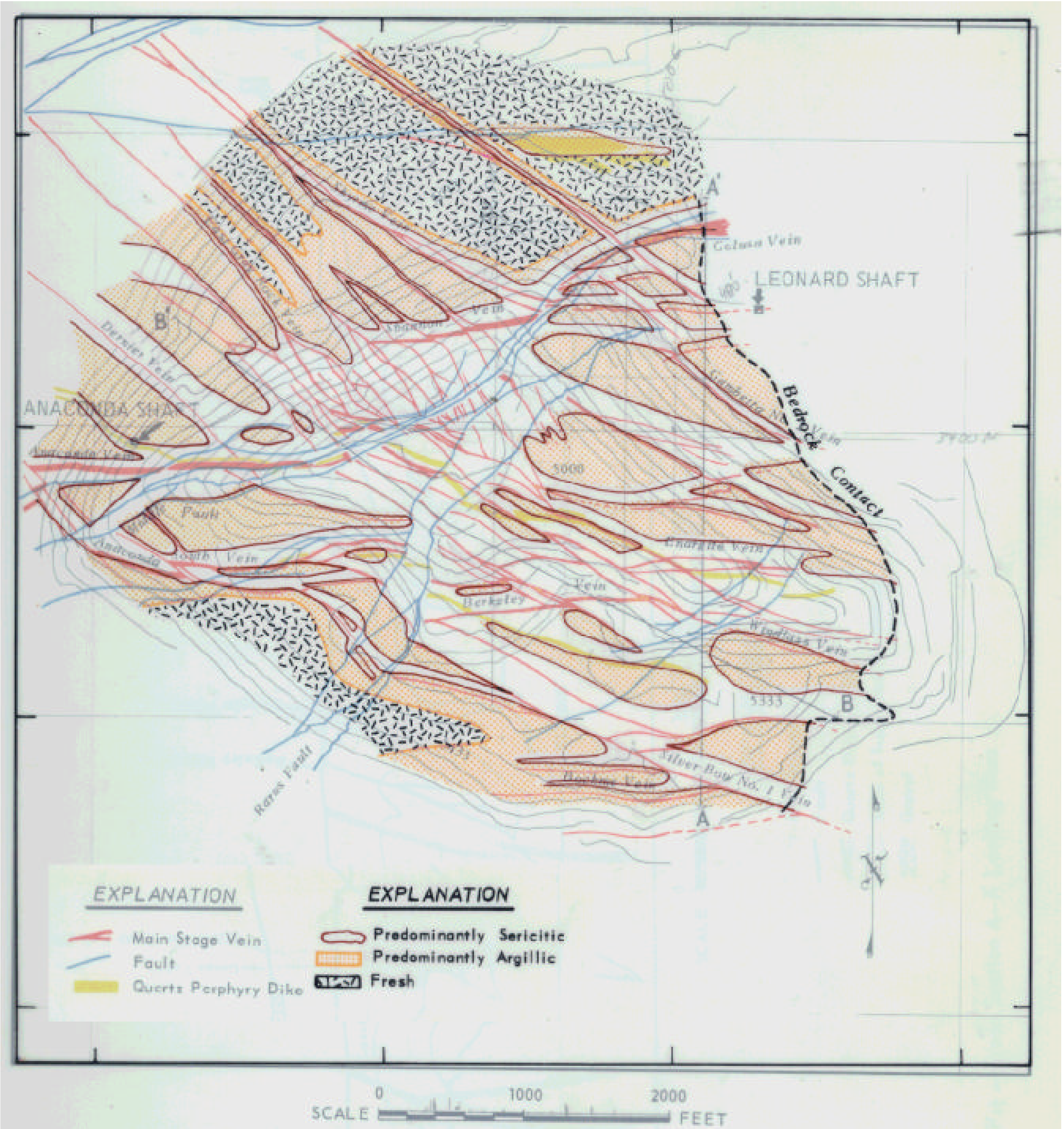

Figure 5. Relationship of alteration to Main Stage veins in the Berkeley Pit, Butte, Montana (McClave, 1973)

Based upon plan maps, vertical cross sections were drawn to show the hypogene and supergene leaching and enrichment zoning used in production and ore control (Figure 6.)

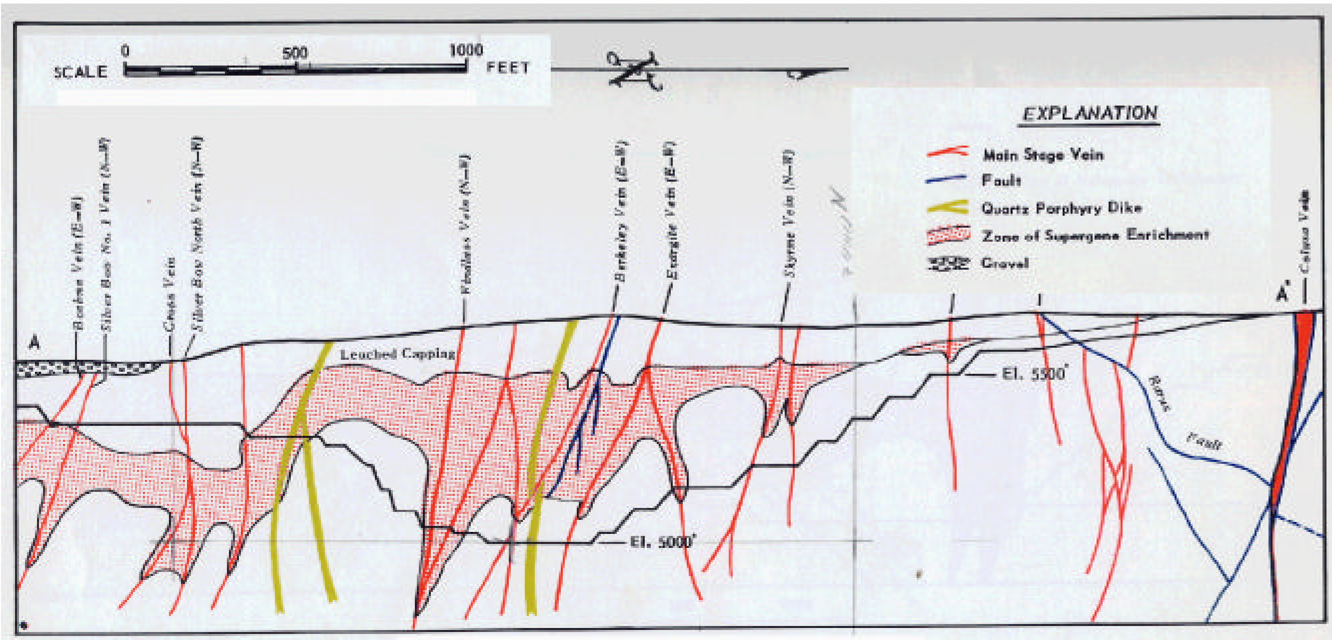

Figure 6. Vertical north-south cross section of Butte Montana mining district looking west (McClave, 1973).

Mapping in Academia

To prepare students for this growing geological field, systematic field mapping classes for undergraduate students were instituted in the US and Canada; one of the first in 1892 at the University of California, Berkeley by Professor Andrew Lawson. Over the next half century, training in surface mapping evolved (Derry, 1947) and remains a requirement in the curricula of most earth science programs including intensive summer field project training following a mapping methods class. Three kinds of information uniquely accessed in the field are addressed: direct observation and measurement, age relations and interpretation (Compton, 1985). Professor Compton's (1985) book became the standard field manual for generations of geology students. Field camps still provide the main systematic training of young geologists to address district scale investigation and often provide the most vivid first-hand realities of concepts learned in the classroom. This evolution in mapping and ever-increasing use of maps in earth sciences, means that the challenges facing digital mapping are considerable and demand an exacting set of standards of digital systems, flexibility, adaptability. Digital mapping cannot compromise these professional standards and succeed. At UC Berkeley today we have completed three years of digital mapping following training with paper methods.

What we do in the Field and How We Map

To offer more than a generic graphical tool pad with device drivers for pen input and control of electronic instrumentation, it is essential to design a geological user interface around the practical needs of earth scientists and engineers to map field relationships and to produce finished maps and data bases as part of our daily workflow. Fundamentally, all mapping is a reasoned abstraction; a simplified scaled rendering and projection of complex reality made visible through observation on the small scale of exposures which are mapped on larger scales onto a chosen plane of projection as a representation. We reduce four dimensional space-time to a two dimensional plane with line, area and symbol attributes to convey time. Orientation and numerical data are related to symbols. How and what we map are determined by our purpose, map scale and time frame. In adapting digital tools for mapping, there are advantages in retaining traditions in so far as they remain useful and provide familiarity and continuity that aid mastering a new digital system.

Interactive Feedback in a Continuum of Geo-spatial Activity

In the process of developing GeoMapper to implement mapping in a style even approaching the practicality and level of excellence developed over the twentieth century in agencies, industry and academia, one is forced to confront the profound complexity of what we geologists actually *do* in the field and call "geological mapping." Geological mapping is the practice of rapidly and systematically delineating, classifying and recording a complex variety of natural geological features in an organized and disciplined fashion applying the scientific method of hypothesis testing using graphical relationships. The body of necessary knowledge is immense. Cognition and spatial problem solving is an on-going part of mapping which is then, intrinsically, a real-time process. Through the process of mapping, new insights continuously emerge from the map patterns which provide guidance as to what features to map next, which direction to go next, and which multiple working hypotheses to entertain until one proves superior to the others. Hence, geological mapping is an interactive, real-time scientific discipline which accommodates identification of complicated geo-spatial and temporal features, flexibility in interpretation, error assessment in making interpretations, and managing unforeseen complexity in the earth as it unfolds on a developing map.

The Mapping Continuum and the Visual User Interface

Translated into a digital formalism, mapping proves to be a great deal more than what is often referred to in the digital media world as "field data capture, 3-D modeling, GIS analysis, data base management or visualization." Mapping is, in practice, *all* of these processes undertaken together simultaneously in real-time outdoors or underground immersed in nature. Mapping is *not* a sequence of discrete point measurements although to non-geologists it may appear so as we walk form place to place. Instead, mapping is a continuum of activities requiring one to keep oriented, located, and continually aware of their lithological and structural environment as we proceed across the landscape or work in an underground drift.

In the transition from paper to digital records, the continuum of mapping has been to some extent *disintegrated* into separate component parts so that each component can take advantage of a specific digital tool; some in the office and others in the field. In making a digital mapping field system however, all the parts need to function together in harmony and be readily accessed and implemented in the routine that mappers deem convenient and essential to workflow and throughput. The problem is that while technological adaptation and substitution can mimic and replace certain traditional mapping procedures, we need to *reintegrate* the component parts of the new digital technology *around* the actual activities of the scientist in the field using the visual user interface and pen stylus as the sole control. Our focus has been on finding the most *direct* means of mapping using digital technology with as few interruptions and departures from how we normally map.

Digitizing Tools

GeoMapper uses a variety of digital tools including Strata Software's PenMap as a digital graphical tool implementing powerful components of mapping in the style of an "electronic plane table." In computer usage these tools are points, lines, symbols and areal pattern and color attributes which are located graphically as geo-spatial features. Through the GeoMapper visual user interface we organize such raw graphic tools and file structures into geological formalisms such as lithology, formations, structures, samples, mineralization and alteration around mapping procedures. Device drivers for using digital GPS and laser equipment in surveying are also an integral part of the PenMap tool package.

GEOMAPPER UNIVERSAL'S ARCHITECTURE

GeoMapper uses several computer programs to execute the mapping process in a manner consistent with established procedures, preferred work sequences and efficiency sufficient as to be considered practical. Since the earth is complex and geology enormously varied, organization is the critical issue to rapid startup, workflow, compilation, data management and map production. GeoMapper Universal provides users a range of organizational features which (1) simplify personalization for local geology around a project orientation, (2) implement geological mapping in either plan and arbitrary section views, (3) separate common mapping activities used most frequently from those that are used only occasionally, and (4) export and manage data files.

Project Manager

The GeoMapper visual user interface is logical and largely self explanatory from the standpoint of a geologist. The first activity in starting a new mapping project is to investigate and define the local geological stratigraphic column. Once a digital mapping legend is created, a user does not need to go back though this step whenever they start a new days' mapping. Hence, we have combined these two steps into a single Project Manager startup screen in GeoMapper Universal (Figure 7).

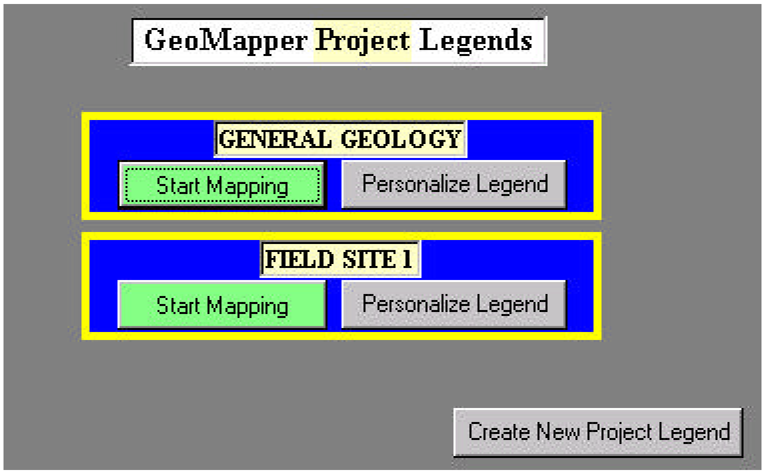

Figure 7. **Project Manager** is the first computer screen of GeoMapper Universal. With it, one elects to either make a new mapping legend or start mapping.

The screen shows the names of the Projects, here as "general geology." By clicking on Create a New Project Legend, a new project title can be added to the list and selected at will from all those created. Then click either on Start Mapping or Personalize Legend to proceed.

Legend Maker

The stratigraphic section in an area of interest is the geologist's link with time and process and defines the units to be mapped. In any region of the U.S., the local stratigraphic section can be easily downloaded digitally or retrieved conventionally from the Correlation of Stratigraphic Units of North America (COSUNA) (Childs and Salvador, 1985) from the AAPG Bookstore. To create such a legend in GeoMapper we use Legend Maker which is implemented when one clicks on Personalize Legend in the Project Manager (Figure 8). To personalize the legend a user simply needs to use point and click skills to effect changes in the design of the formation and lithology buttons, select their area fill patterns and/or colors, and type-in their descriptive names. Typically this process takes less than an hour. A hard copy of the legend can be printed. This Legend Maker feature of GeoMapper removes the most serious barrier to using digital mapping: that of readiness to map.

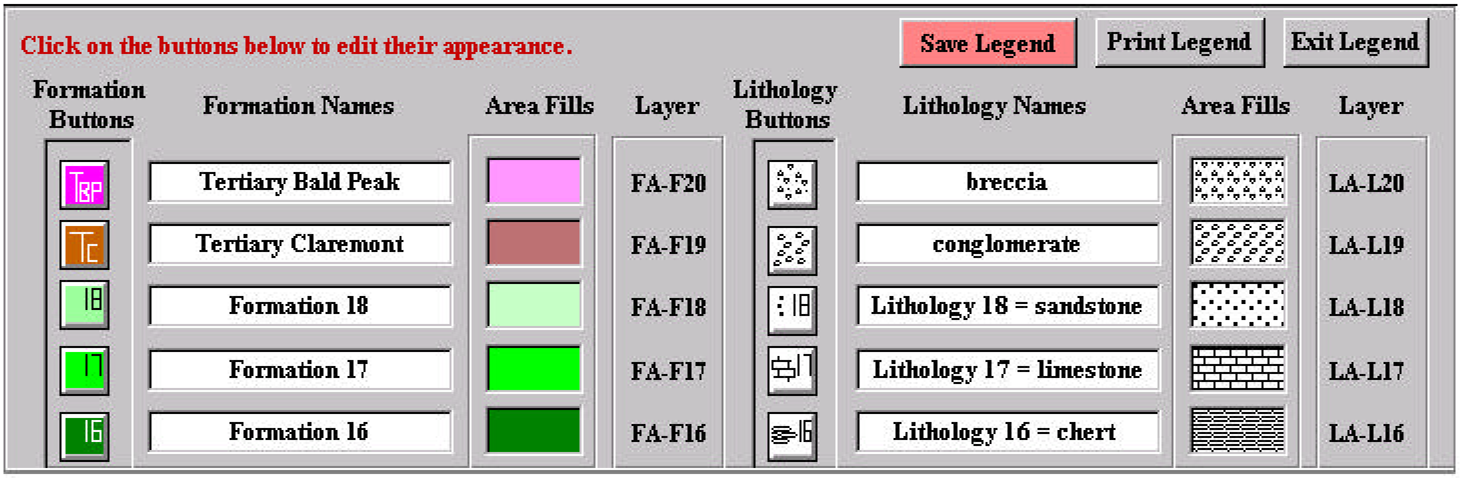

Figure 8. **Legend Maker** is shown here, partially completed by a user. This is where the local geology of a project is entered in terms of lithology, formations and age sequence, using only point and click methods. The Formation buttons use the standard geological time scale symbolism with Epoch or Period in caps and subscript initials for the formation name. The Lithology buttons show the pattern used for that rock type.

Start Mapping

Once the geological legend has been made, one clicks on Start Mapping on the Project Manager window (figure 7). From this point on, GeoMapper's visual user interface shows arrays of buttons arranged so as to provide a logical, self-explanatory set of features used in mapping.

Button Tool bars

Tool bars are arrays of buttons which can be touched by the pen stylus to implement mapping steps. A combination of color coding, grouping, sequential ordering, and button design make it possible to begin mapping in a very short time, often less than a few hours. The organization of the visual interfaces is designed around the requirements of mapping practice. The structure of the files created within project areas is consistent with extraction of information to solve real geological problems. Immediate results are accomplished by provision of user protocols offering the basic geological formalisms organized into like features: lithology, structure, formations, mineralization, alteration and sampling sites that collectively constitute the essential and complex geo-spatial and temporal features contained in geological maps. Toolbars increase the speed of mapping considerably.

Logic behind Color-Coded Button Mapping

GeoMapper's architecture implements mapping tools with buttons, in contrast to pull-down menus which can interrupt the thought process of mapping and leave you stranded as to what to do next. GeoMapper includes only the commands necessary for preparing a map file in which mapping can be accomplished with the variety of mapping tools expected in geology. Furthermore, the buttons are shown in the general sequence of their use so that scientific logic guides the selection of mapping tools. Button color-

coding facilitates eye and hand coordination when selecting frequently used buttons from a feature group or to point out important buttons in a sequence group. We use a stop light method with green, yellow and red phases of activity. **Green** buttons refer to the most commonly used buttons in geological mapping. Yellow buttons refer to procedures that are used only rarely, for example if you need to erase or undo the last work. **Red** buttons refer to procedures that are essential to do before you stop mapping, for example saving your files or doing export of critical files. Other colors refer to special use functions. **Light blue** buttons refer to a sequence of steps to map base maps. These buttons are used only once in a project. **Purple** buttons group instruments like GPS and lasers into setup buttons to select the instruments, and turn them on and finally turn them off. **Magenta** buttons manage section view mapping functions and all algebraic transformations done in GeoMapper.

Button Mapping Starting With the Master Toolbar

GeoMapper tool bars contain both the geological features needed to map the earth as well as a visual interface to use all the digital electronic equipment a user selects. The first tool bar which appears, Master Toolbar, manages maps and instruments, and the taking of rock, soil, and water samples and infrared spectra (Figure 9).

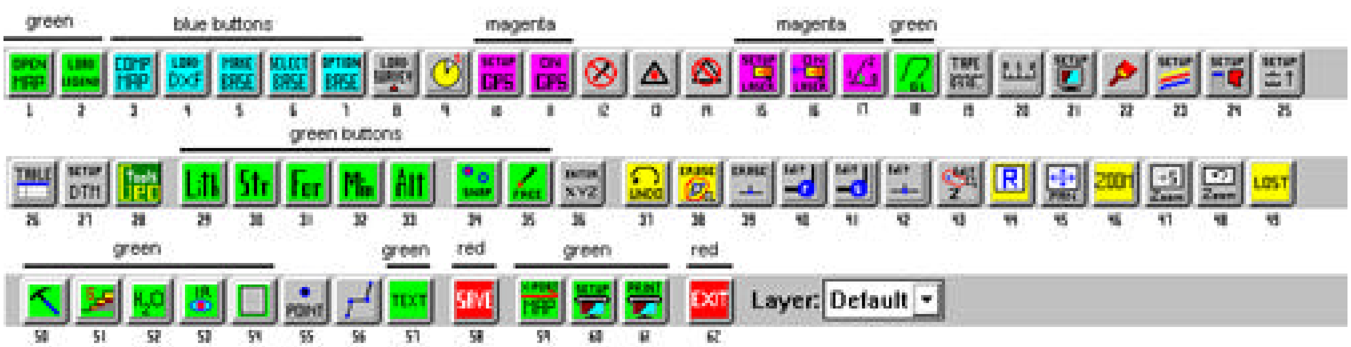

Figure 9. **Master Toolbar**: Numbered buttons are; 1- Open Map file, 2- Load a Legend Toolbar (configuration), 3- Compile Maps , 4- Load DXF file (vector graphics), 5- Make Base Map (vector base map made out of loaded vector graphics), 6- Select Base Map, 7- Set Base Map Options, 8- Load Survey Points, 9- Set AutoSave timer, 10- Select GPS, 11- Start GPS, 12- Methods of Input Off, 13- Survey Point, 14- Survey Graphics Off, 15- Set LASER, 16- Start LASER, 17- ID Angle correction for LASER, 18- Map Ground Line w/ LASER, 19- Plot Survey Tape, 20- Plot Map Scale, 21- Set Map Display Options, 22- Paint Buttons Utility, 23- Layers Tool box, 24- Set GIS Table Options and Area Fills (transparency), 25- Set Symbols (default size and orientation), 26- GIS Table (Form Generator) Utility, 27- Set DTM Parameters, 28- GeoMapper Tools Toolbar, 29- Lithology Toolbar, 30- Structure Toolbar, 31- Formations Toolbar, 32- Mineralization Toolbar, 33- Alteration Toolbar, 34- Snap node for instrument method of input, 35- Free node for pen method of input, 36- Type-in coordinate data method of input, 37- Undo/Redo graphics input, 38- Erase graphics (drag a polygon to select graphic nodes), 39- Erase symbols, 40- Move individual polyline nodes, 41- Move individual polyline nodes, snapping onto other nodes, 42- Move, rotate, or resize symbols, 43- Edit the elevations (drag a polygon to select graphic nodes), 44- Redraw the map graphics, 45- Pan the map , 46- Zoom Utility box, 47- Zoom in/out to the previous view, 48- Zoom out by five, 49- Zoom out to show all of the map, 50- Plot Rock Sample, 51- Plot Soil Sample, 52- Plot Water Sample, 53- Plot Infra-Red Sample, 54- Plot Notes reference, 55- Plot Point graphic , 56- Plot Polyline graphic, 57- Plot Text graphic w/ settings , 58- Save Map file and Legend changes, 59- Export Map for Compilation, 60- Setup Printer and Paper size, 61- Print Map file, 62- Exit Map file

In the GeoMapper button interface shown, referenced to numbered buttons in parentheses, a mapper begins using the buttons located in the upper left corner and proceeds across this row towards the right and eventually onto the second row. In support of the sequence logic, features that are essential to a mapping project including data entry are color-coded with green buttons. The save and exit features are colored red as they are crucial steps when working with digital map files and must be implemented before exiting. The most frequently used buttons from the editing and zooming feature groups are color-coded yellow. The base map preparation sequence group of buttons are color coded-cyan, and the instrument communications group (GPS and Laser) is colored magenta. The initial map file preparation runs through a sequence of buttons beginning with opening up a map file (1); loading the mapping legend (configuration) (2); compiling and selecting base maps and setting their display parameters such as using a digital topographic base map either with or with an ortho-photo show (3-7); loading survey points (8); setting the automatic saving timer (9); setting the mapping units (meters or feet), projection types, and datum for the GPS (10-11); turning off previous methods of input (12); plotting a survey point (13); turning off the survey point graphic (14); using the laser range finder (15-16) and the magnetic declination correction use laser back site correction (17) to set the declination on the laser, then mapping a ground line with the laser (18); plotting the survey tape (19) and the scale bar (20) for scale orientation; and, setting the display screen parameters (21). From this point, the mapper can then proceed directly to the second row and use the Lithology (29), Structure (30), Formation (31), Mineralization (32), and Alteration (33) buttons to open their respective mapping tools as needed. When the Lithology (29), Structure (30), Formation (31), Mineralization (32), and Alteration (33) buttons are touched by the pen stylus, each expand to show their own tool bars. Use of sequential tool bars reduces the amount of computer screen display used up by the legend and maximizes the area of the map.

Lithology Toolbar

Lithologies can be mapped either as lines with different styles or as patterned infills. Clicking on the Lithology button causes 20 Lithology (1, 2, …. 20) buttons to show on the right of the **Area** button as area fills and 10 of those Lithologies (1, 2, …10) that can be mapped as lines found to the right of the **Line** button (Figure 10).

Figure 10. **Lithology Toolbar** shows the local rock types in an area, in age sequence. Lithologies can be mapped either using a line style or areas filled with patterns. Buttons are changed automatically by a user when they use **Legend Maker**.

The buttons are arranged in an age sequence that decreases as you move to the right on the toolbar. Button number 1 is marble, 2 is quartzite, 3 is serpentinite, 4 is

peridotite, 5 is gabbro, 6 is granite, 7 is porphyry, 8 is diorite, 9 is tuff, and 10 is schist before any personalization. The lithological patterns programmed follow Compton (1985). The Lithology toolbar also contains the basic structural features of contacts and strike and dip so that a mapper needn't change tool bars while doing the most basic mapping activities. This saves time.

Structure Toolbar

Clicking on the Structure button brings up a full set of structural symbols given in both azimuthal and down-dip methods (shown with a D) (Figure 11). When a symbol is selected, the mapper enters azimuthal and dip data. The program then plots the symbol in its correct orientation automatically. Contacts are shown in black, faults in blue, veins in red and fold axes in black. Dashed lines represent uncertain positions of these features. Different thickness of faults and veins are given as separate buttons. Structural symbols include contacts, faults (normal, thrust), strike and dip, horizontal beds, vertical beds, cleavage, foliation, trend and plunge, plunging anticline, and plunging syncline.

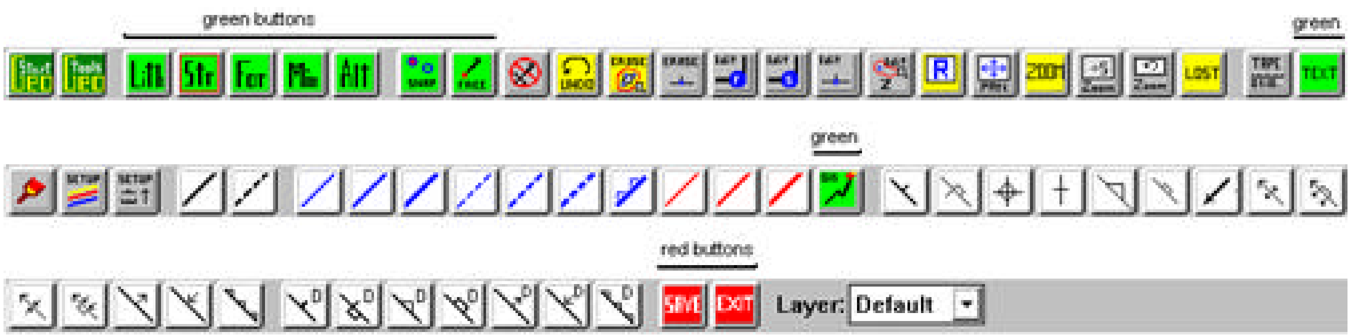

Figure 11. **Structure Toolbar** shows the common structural symbols used in mapping: contacts, faults, veins, strike and dip, horizontal and vertical beds, foliation, joints, trend and plunge, anticlines and synclines, and down dip direction versions of the same symbols entered alternatively as azimuth and dip.

Formations Toolbar

The Formation button causes 20 Formations (1, 2, …. 20) buttons to appear (Figure 12). The buttons are arranged in sequence of age with the youngest on the right end of the toolbar buttons. Formation color infills are often completed in the office by snapping onto the nodes along contacts. This makes a sharp demarcation of color on both sides of the contact line with no gap. Coloration of the entire map by formation using this toolbar creates the most visible attributes of completed geological maps.

Figure 12. **Formation Toolbar** shows the local rock formations in an area in age sequence. Buttons are changed automatically by a user when they use **Legend Maker**.

Mineralization Toolbar

The Mineralization button brings up a suite of oxide and sulfide facies mineral symbols that are used with the four mineralization style buttons representing dissemination, veinlets, stockworks and breccias (Figure 13). Oxides facies minerals include calcite, quartz, limonite, hematite, goethite, cuprite, tenorite, pyrophyllite, and kaolinite. Sulfide facies minerals include galena, sphalerite, tenantite, pryrite, bornite, chalcocite, chalcopyrite, covellite, digenite, enargite, molybdenite, and anhydrite. These features are customizable.

Figure 13**.** **Mineralization Toolbar** shows common ore minerals and mineralization styles.

Alteration Toolbar

The Alteration button brings up two sets of buttons for Propylitic, Argillic, Potassic, Sericitic, Advanced Argillic, Silicification, Garnetization, and Carbonation facies of hydrothermal alteration (Figure 14). The first set, is used to map alteration as a color-coded **line** and the second set is used if you prefer to map alteration as a color-coded **area**. These features are customizable.

Figure 14. **Alteration Toolbar** shows the most common types of wall rock alteration: propyliti,c, argillic, potassic, sericitic, advanced argillic, silicification, garnetitization, and carbonatization entered either as lined patterns or alternatively as areas infills.

GeoMapper Tools Toolbar

This tool bar opens up the final set of buttons shown in Figure 15 in magenta to map in geology in section view, for example when the side walls in mines or exposed cliff faces, or road cuts in any orientation besides plan view. This type of mapping is usually done using a digital photograph as the base map so our mapping tools can be used to trace contacts and add infill patterns. With the laser set up and located using the GPS for positioning and its declination corrected for local magnetic declination, the Capture Photograph button (1) can be used to download an image from a camera to register the direction of the photo, the date of the snap shot, and a description. The next button is the Field GeoRef Points button (2) which opens an instruction window for geo-referencing the photo in the field using the Laser. The Plan Map View button (3) will guide you in transforming (4) the field geo-reference points which are imported by the GeoReference Image button to create a section view georeference. The Raster BaseMap Utility button (5) will use the section view geo-reference points to create a base map of the image. Finally a section view frame (6) is defined around the image base map by following the instructions of the Section View Frame button.

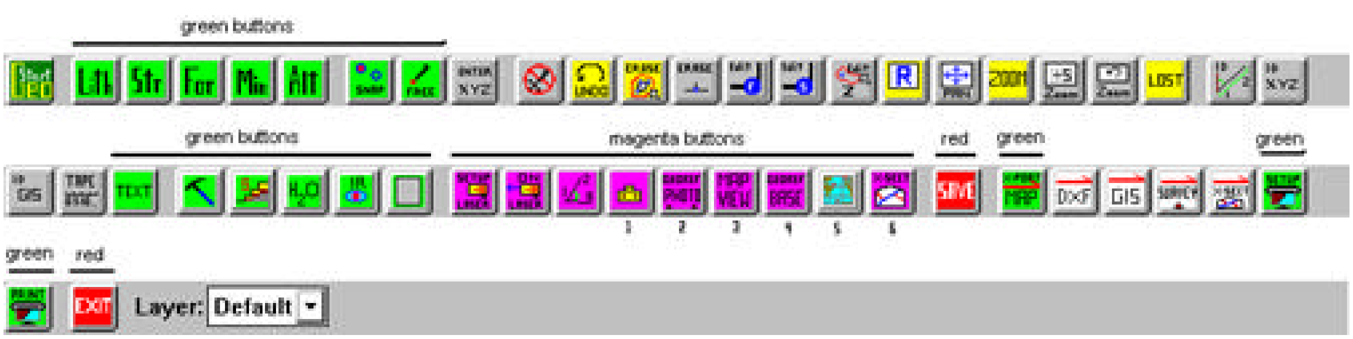

Figure 15. **Tool Toolbar** contains special features such as those necessary for mapping in section and exporting completed maps and numerical data bases.

Section Mapping Algorithm

Although we typically map in horizontal plan view in GeoMapper, we can map in any arbitrary section by user matrix algebraic transformations that we have coded in Visual Basic. This is done by taking a digital photograph of the inclined surface you wish to map and measuring the orientation of the inclined surface (Figure 16). A laser is used to locate georeferencing points on the photo. Using rotation matrices, we rotate the plane of the photo into horizontality where we map as though it was inclined using the full geological legend. When the mapping is complete, we simply undo the rotation by another matrix transformation and restore the section to its proper position.

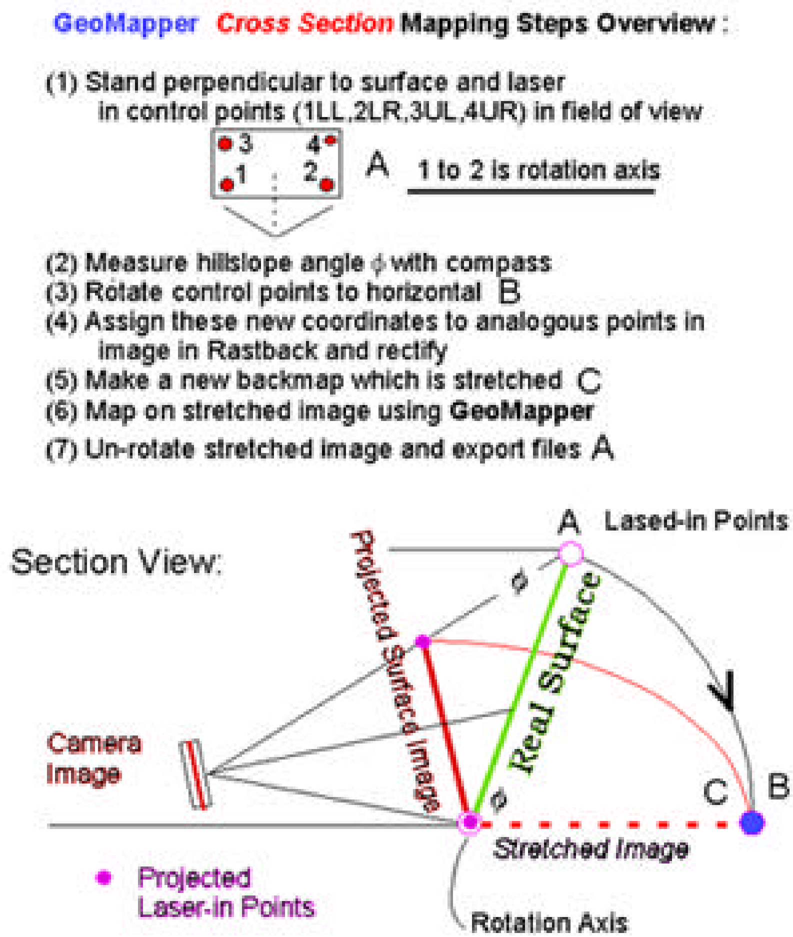

Figure 16. Geometry of the section mapping algorithm used in GeoMapper Universal, as accessed from the **Tool Toolbar** .

Scientific Logic and Uncertainties

As in mapping with traditional paper and pencil media, GeoMapper has been designed to implement the fundamental guidelines of the scientific method including rigorous separation of fact and interpretation by showing uncertainty. This is done by modulating line character from being solid where contacts are well-located and dashed where they are inferred. The outline of outcrops can also be mapped separately from a color infill which covers the entire area underlain by a given formation. This is a

powerful and novel feature of GeoMapper as the outcrops record the primacy of the data on which interpretations are based (Figure 17).

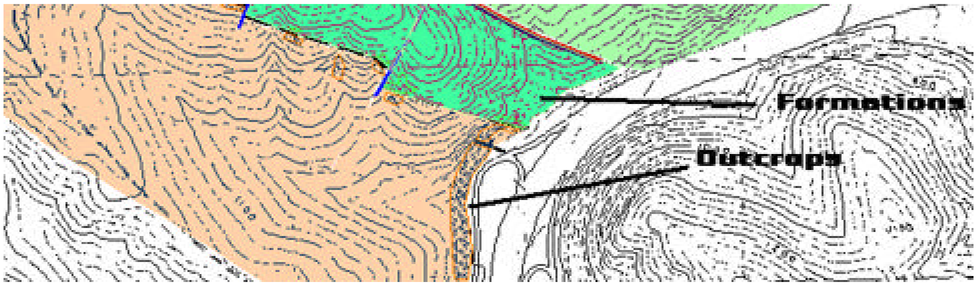

Figure 17. Miocene geology near Highway 24 in Berkeley showing outcrops and formations.

Map Scale and Spatial Resolution

We have constructed scale bar symbols which can be placed anywhere on a map when needed. By mapping small-scale data-rich features like outcrops separately from the overall formations, a map may be drawn at any scale appropriate for a question at hand. When one zooms out, those features may be too small to see at a broader scale, but they are preserved and can be shown on a detailed scale by zooming back in.

Map Compilation and Bi-directional Data Transfer

Digital mapping creates new scientific knowledge. The original map with its contacts modulated for the level of certainty, outcrops and color formation infills, represents this knowledge in its purest, primary form. Geographic Information Systems (GIS) can process primary data inputs created by mapping, and in so doing, are useful printing output, data storage, and interpretive tools. In that respect, GeoMapper Universal can be viewed as the front end of GIS systems. Compilation of maps as new map information is available can be done either within GeoMapper as a growing aggregate map file or exported as small sub-areal maps to GIS systems. GIS information can be ported into GeoMapper including base maps, ground lines, and survey point data.

Map Production

At UC Berkeley, we have produced digital maps for three years including field methods training and summer field camp. We output reports, maps, cross section and field photos in folio format following the tradition set by the USGS while implementing

the detailed mapping system of the Anaconda Company at the dawn of the 20th century (Figure 18).

Figure 18. Poster sheet for Berkeley Hills geology map with report on the left, map and cross section center and digital field photos on the far right.

Conclusions

In the hands of a practiced field geologist, GeoMapper Universal can now produce good quality geological maps in a reasonable amount of time with a minimum of training and no knowledge of computer programming. Once students are trained in paper mapping methods, they too can readily learn digital mapping with GeoMapper Universal. Poster or folio map productions combining maps, text, cross sections and photographs are easily made with PageMaker rendering completed project work in a compact and vivid format faithful to our century-long and distinguished mapping heritage but now part of the information age using the digital-electronic tools of the day. The time savings is in the full sequence of activities from field mapping to final digital map by eliminating the intermediary steps of paper media and digitizing. Information is not lost. Access and sharing by other users is immediate once the digital records are put on line. Digital mapping takes some time to reach this level of efficiency. One of the most important advantages of GeoMapper supported by PenMap is in its capability of simultaneously integrating digital topographic maps, ortho-photo base maps and any vector map (eg. Geophysical data) thereby providing the capability of remote sensing and geo-spatial interpretation on a pen computer. All things considered, digital mapping skills should contribute to a mapper's professional development and make their job more efficient and their maps more readily useful.

Acknowledgements

While many institutions wait until geological mapping software is commonplace and inexpensive, the early innovator institutions who have sponsored applied research within the Berkeley Earth Resources Center Digital Mapping Lab to develop the systems incrementally deserve special recognition of the important role that they have played in assisting those of us who develop systems for mapping. Furthermore, rigorous field testing and procedures have also been worked out mutually with our sponsors. The

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Vendor Data

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